MESUR PATHFINDER MICROROVER FLIGHT EXPERIMENT:
A BETTER, FASTER, CHEAPER ROVER'

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Mars Rover missions have been studied since about 1985, primarily in conjunction with Mars Sample Return or as precursor explorers for human missions. Until 1989 the rovers envisioned for these missions were large (800-1000 kg) and highly autonomous. in 1989-1992 funding for human missions and their robotic precursors was steadily cut by Congress. This funding shortfall forced innovative concepts to be developed for Mars Rovers, and the most promising of these concepts focussed around small ("mini" to "micro") rovers in the 5 to 50 kg class.

Four factors contributed to the feasibility of small rovers:

1. The worldwide miniaturization of electronics.
2. The availability of small, extremely mobile chassis developed as test models for the large rovers at JPL.
3. The development of insect-like autonomous control algorithms, initiated by Rodney Brooks of MIT with his "subsumption architecture" and extended by David Miller and others at JPL.
4, The development of the "Computer Aided Remote Driving" technique of remote operator control at JPL.

These factors were combined at JPL in a series of experiments where increasing smaller computers and increasingly sophisticated sensors were mounted on increasingly capable "Rocker r-Bogie" chassis. Called "Rocky" for short, this series culminated in a demonstration in June 1992 of

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"Rocky 4" which proved the concept of an integrated microrover system (7 kg including instruments) and which led to funding by NASA OACT (Office of Advanced Concepts and Technology) of a MESUR Pathfinder Microrover Flight Experiment (MFEX).

MFEX will be carried by the Mars Environmental Survey (MESUR) Pathfinder mission to the surface of Mars, where it will perform technology, science and MESUR mission engineering experiments, MESUR Pathfinder is funded by NASA Office of Space Science (0SS) and is cost-capped at $150M (FY92$, Phase C/D), MESUR Pathfinder will launch in December 1996, with a single spacecraft which will fly directly to Mars, enter the atmosphere with a Viking-derived heat shield, and land with the aid of parachutes and airbags. Landing will occur in July 1997,

The Micro-rorover Flight Experiment is cost-capped at $25M in real year dollars for Phase A through operations, and is not included in the $150M MESUR Pathfinder costs, For lowest cost, the basic Rocky 4 design was selected as the starting point for MFEX rover design. This features 6 powered wheels attached by a set of "bogie levers" to a single body. The front and rear wheels are steered via Ackerman steering (like an automobile), Control is shared between earth (operator target designation based on stereo images sent from Mars) and the rover (autonomous "behavior" control using on-board sensing for path following and hazard avoidance).

The information gained from MESUR Pathfinder will allow selection of the optimal concept for future Mars rovers for MESUR Network and Mars Sample Return missions.

MESUR Pathfinder will be launched on a Delta and the spacecraft will provide support services to the rover from launch through landing, After impact the lander will open, positioning the panels so that solar energy can be collected and the rover is poised for deployment.

The lander camera will take a panoramic image of the surroundings and transmits it directly to the earth at a few hundred bits per second. (MESUR Pathfinder has no orbiter, and Mars Observer cannot be relied on as a communication relay), The rover will be released and will erect itself and move down deployment ramps to the surface. It is thereafter independent except for using the lander data and communications functions for command and telemetry.

The rover has three primary mission objectives:

1. Technology Experiments
2. Science Experiments
3. Mission Experiments

The technology experiments are to determine microrover performance in the poorly understood Martian terrain. Technology information is collected by instrumenting the rover mechanisms to determine wheel-soil interactions, detect hazards, determine navigational errors, etc. Because the rover is part of the MESUR Pathfinder payload it will also gather science data by deploying an alpha-proton-x-ray spectrometer (APXS) against one or more rocks, and possibly soil. Finally, because MESUR Pathfinder is an engineering test of a transport and landing system for Network, the rover will image the lander to allow its condition to be assessed.

Both the lander and the rover have limited redundancy and the thermal environment of the Martian surface is very harsh (O **to -100"C** daily cycles). So the surface mission design must achieve the important mission objectives in a relatively short time (goal = 7 days). The lander-to-earth direct communications link is limited to a few hundred bits per second, even **using a lander high** gain antenna, and therefore information to re-direct the rover can only be gathered after a whole sol's transmission. (A "sol" is a Martian day and is about the length of an earth day). Consequently the rover can only be commanded once per day.

Surface mission design is by scenarios, with timelines built around data transmission capabilities. A baseline scenario has been constructed for planning the data transmission and storage requirements for both the lander and rover, In this nominal scenario the rover is deployed on the first sol. The rover is directed toward a target rock, pausing to perform soil mechanics experiments and image the lander.

The next sol is consumed directing the rover to contact the rock and place the APXS on it. The rover position will be determined relative to the target at the end of each sol by imaging it from the lander. The APXS spectrum in this scenario is taken overnight, to conserve the daylight hours for rover movement. The overnight spectrum will be powered by the rover's batteries, An APXS soil measurement may be taken first.

The prime mission scenario includes three lander images and multiple APXS measurements and technology experiments, all within about 10 meters of the lander (within the highest resolution lander images). For the extended mission the rover can be risked on longer traverses. It can even head "over the horizon" (out of range of the lander's camera) by using its own images for navigation.

The rover is controlled by an earth operator who views a work station with a stereo display of the lander's (or rover's) image of the terrain through 3-D glasses, The work station's software allows an icon of the rover to be placed in the scene and the coordinates of this placement determined. These coordinates form the basis of the rover traverse commands, Commands which enable rover tasks, e.g. "perform a soil mechanics experiment", "place the APXS on a rock", are interspersed with traverse commands and sent to the rover through the MESUR Pathfinder Mission Operations System (MOS). The commands are sent, shortly after sun and earth rise on Mars, to the lander, which forwards the commands to the rover over the UHF link, and the rover stores them for execution.

Rover telemetry, including images, is stored, compressed and packetized on the rover. The rover notifies the lander when it is ready to transmit, and the lander o.k.'s transmission when it is ready to receive, Telemetry packets are downlinked over the rover-to-lander UHF link and the lander stores the packets for transmission to earth.

MFEX is an example of a "Better, Faster, Cheaper" NASA activity, Consequently the rover's design and new processes for implementing it are being developed concurrently. The focus of the cost constrained activity is a deliberate constraint on computational power, coupled with new autonomous control software technology and sensing/control architecture. Performance and risk are variables to achieve the costs constraints (for example, low-speed computing is enabled by slow rover speeds).

'i he selection of affordable parts and a cost-constrained design are built around the low performance computer and its advanced autonomous software. This includes the extensive use of low-cost (by space standards) commercial and Mil-standard components. Around that are wrapped cost effective processes: a small, low overhead team; rapid prototyping/ concurrent engineering; new processes for parts qualification and procurement; and selected industrial participation for cost-effective technology transfer.

In order to meet the cost constraints, and since the mission duration is relatively short and the radiation environment relatively benign, the rover will take selected design risks, such as maximizing the use of off-the-shelf parts. New classification and qualification procedures are being developed at JPL to minimize the cost of using such parts. Class S, flight qualified, parts are used where ever cost effective, e.g. the CPU and I/O board will be Class S. Block redundancy is practically nonexistent, but considerable functional redundancy is used, e.g. solar panels and primary batteries.

As part of the low-cost process for MESUR Pathfinder the End-to-End Information System (EEIS) is being developed using a concurrent engineering process. The rover operations development is an intimate part of this process and is the focus of the earliest Pathfinder EEIS design and test activities.

The MFEX activities are built around a rapid prototyping approach. "Rocky 4" was stripped to the bare chassis for mobility testing (Rocky 4.1) in sand and lunar simulant. Motors and mechanisms closer to flight were added for these tests, and then the chassis was given to the control subsystem, Control breadboarded a complete suite of sensors and a processor and I/O board, for use in software development. Rocky 4.2, shown on the cover, is now operating under software control in a sandbox and is being used as a software development tool,

In parallel with this system development, component selection and testing are proceeding, For "example, commercial motors and gears are being evaluated in a small thermal-vacuum chamber for their resistance to frigid Martian conditions, These rapid prototyping activities have been facilitated by a new rapid procurement process developed by JPL's procurement organization to support the “Better, Faster, Cheaper” way of doing business.

The next step in the rapid prototyping process is to procure two sets of flight hardware, storing one set in clean conditions and using the other set to construct a “System Integration Model” or SIM. The SIM will be subjected to field and environmental testing, and will be used for interface checks with the MESUR Pathfinder spacecraft during its Assembly, Test and Launch Operations (ATLO). Based on the SIM results the Flight Unit will be built up, perhaps with some parts modifications, in clean room conditions. This is more arduous than normal spacecraft cleanliness because of planetary protection restrictions. The Flight Unit will be integrated with the flight spacecraft and subjected to flight environmental testing in conjunction with the spacecraft.

The rover has an anticipated mobile mass of 9.0 kg, science instruments add about 2 kg, and another 5.0 kg is allocated for lander-mounted rover equipment, These limits are dictated by the payload capability of the MESUR spacecraft. While the rover has a nominal height of 280 mm (with 130 mm ground clearance), the available lander volume allows only 200 mm, forcing the rover to stow at a static height of 180 mm. The rover is 630 mm long by 480 mm wide. This small size poses considerable challenges for mobility, computation, thermal control, power and telecommunications.

The rover configuration has evolved extensively from the basic architecture demonstrated in June of 1992, although the flight configuration will retain the 6-wheeled rocker- bogie chassis, with the front and rear sets of wheels being steered. The rocker-bogie mobility system was developed over several years using custom computer models developed at JPL, as well as analysis tools such as NASTRAN (FEM) and ADAMS (dynamics code), verified through the development of scale physical models. Although the rover can move through very hazardous terrain relative to its size, it is a very stable platform (when compared to more conventional three body designs) for science, imaging and proximity sensing. For obstacles which it can’t surmount, the rover will depend on its on-board sensing and autonomous control system to find a safe path around them to reach the operator-designated target.

All on-board computing and control functions will be handled by a single Intel 80C85 processor, selected for its low cost and Class S radiation/Single Event Upset resistance, This is only an 8-bit processor which runs at about 100 kips, in contrast to new technology flight processors. However, development to date indicates that it is ample for the rover's needs, provided that rover speeds remain slow. (It is also vastly superior to all computers used by planetary spacecraft before Galileo).

An I/O board is being constructed which can be cheaply manufactured in Class S technology, and in a small, low power package. The processor and I/O board package form a computer which will perform all the computational functions of the rover, from command decoding, to sensor data collection, to control response calculations, to telemetry collection and packetizing. Almost all elements of the computational system are Single Event Latchup (SEL) resistant and the rover design incorporates triple redundancy where SEL susceptibility might exist.

A new proximity sensing technology which is being developed by an OACT technology program is a candidate for use by MFEX. This utilizes the central processor to read out images from commercial CCD's. This system uses ranging information from commercial laser light stripers to identify obstacles, such as large rocks, overhangs and holes. Then autonomous hazard avoidance "behaviors" will **drive the rover around the obstacle.** Other sensors are also used for hazard avoidance, health monitoring, and navigation dead reckoning.

Rover telecommunications is planned to be by means of Mil-Spec, half duplex, UHF modems operating at about 460 MHz and broadcasting over 1 meter-high whip antennas. One modem/antenna is located on the rover, the other on the lander. The lander data system interface with the modem is through an RS 232 port for simplicity. The modem currently being investigated is from the Motorola R-Net series which is low power and Mil-Standard qualified. Communication is possible over several hundred meters, even if the rover goes '(over the horizon" from the lander's view. A new JPL "Class D" parts qualification process is being developed using the Motorola modem as a test case.

Rover power is provided by 0.2 square meters of solar array. This is sufficient to power the rover for several hours per sol, even in the worst conditions of atmospheric dust. The array cells are standard, space qualified silicon, and will be purchased in a common buy with the lander solar arrays for cost savings. As a backup and augmentation, 150 MW of primary, Lithium Sodium Dioxide, D-cell batteries will be enclosed in the Warm Electronics Box.

Power control is relatively complex. The use of a variety of commercial, flight and Mil-Standard parts means that regulated power at a number of voltage levels is required. Power is managed to maximize power margin and simplify system design. All power switching is controlled by the central computer.

Temperature sensitive elements (electronics and batteries) are qualified to -40°C and will be enclosed in a thermally insulated compartment called the Warm Electronics Box, or WEB, which is planned to be a thermal vacuum enclosure to minimize mass. Various materials are being evaluated for the WEB, One or two RHU's may also be used in the WEB. Elements outside the WEB will be qualified to withstand ambient surface temperatures,

MFEX is being conducted as a JPL in-house project because limited funding in the early years, plus the short project cycle and the relatively unproven technologies involved, prevent a system contracting approach. JPL's expertise in small rover R&D is being used to develop the prototypical MESUR Pathfinder rover, which will lead to well-specified industry contracts for future rovers.

MFEX is also a candidate for technology transfer through industrial partnerships for other space mission and commercial applications, and industry interest is solicited.

# AEROSPACE AMERICA FIGURE CAPTIONS

Figure 1 - After impact the lander will open, positioning the panels so that solar energy can be collected and the rover is poised for deployment from one of the petals.

Figure 2 - A baseline operational scenario is being used for surface mission planning and rover/lander telecommunications and power design.

Figure 3 - Rover design and implementation processes are being developed concurrently in a "Better, Faster, Cheaper" approach.

Figure 4 - The rover configuration features a small solar array surmounting a "Warm Electronics Box" thermal enclosure, the whole being made mobile by a six powered wheels connected by "rocker bogies".

Figure 5 - A side view of the rover shows batteries and electronics stowed in the "Warm Electronics Box" thermal enclosure, plus the position of the UHF antenna. The forward CCD's are part of the proximity sensing system. The rear CCD may be included to help position the APXS.

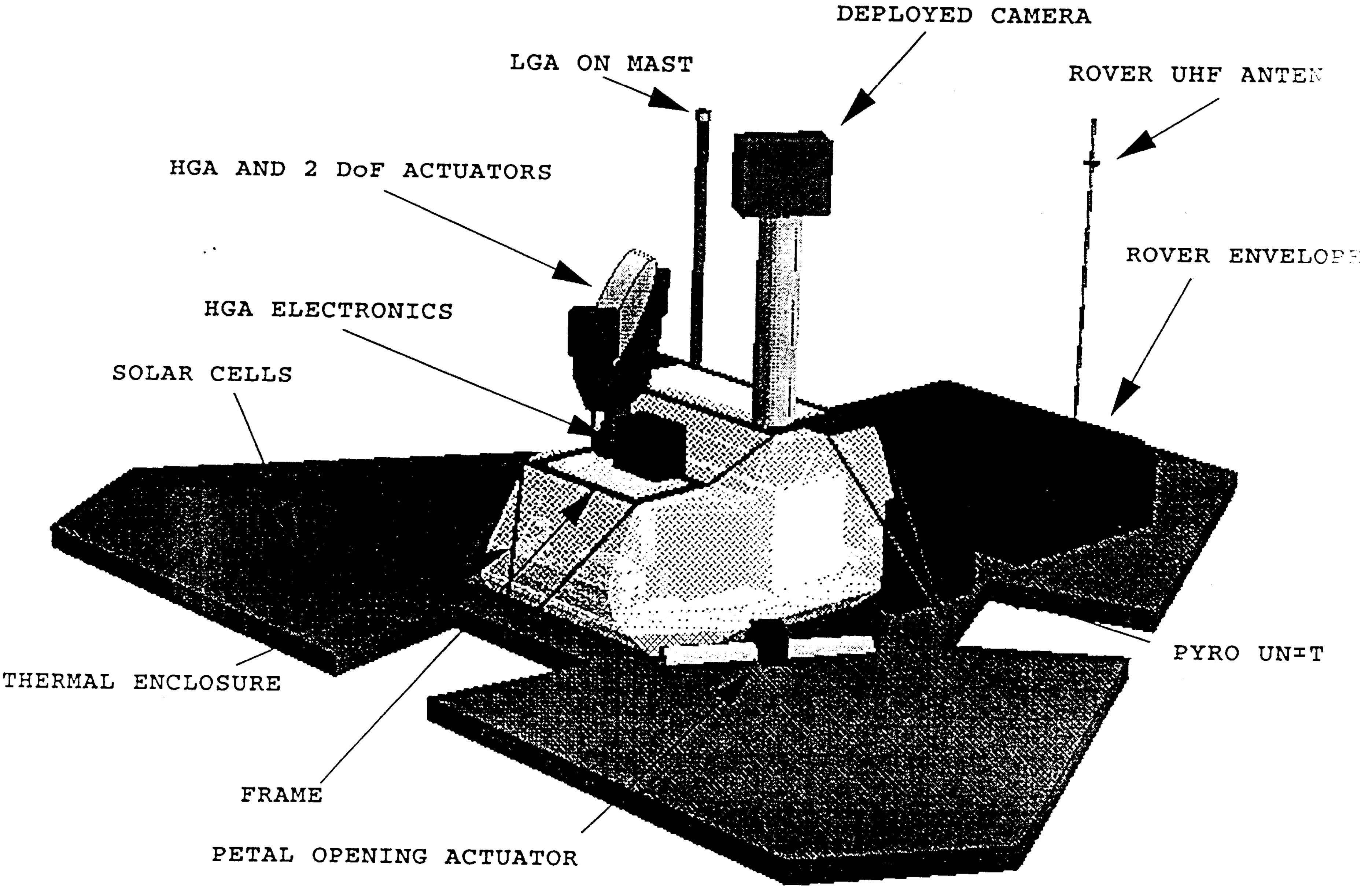
Figure 6 - A top view of the rover shows batteries and electronics stowed in the "Warm Electronics Box" thermal enclosure, The forward CCD's are part of the proximity sensing system. The rear CCD may be included to help position the APXS.

Figure 7 - The rover is "squatted down" in its stowed configuration. This configuration is necessary because of volume constraints until the lander opens on the surface and the rover "stands up".

Figure 8 - A schematic of the rover control system shows the numerous input-output functions that the central processor must control to perform surface navigation, hazard avoidance, and mission/science functions.

Figure 1.

# MESUR PAT×FINDER DEPLOYED CONFIGURATION



# Figure 2

## MESUR PATHFINDER ROVER
## NOMINAL 525 BPS 7-sol SCENARIO, 15°S

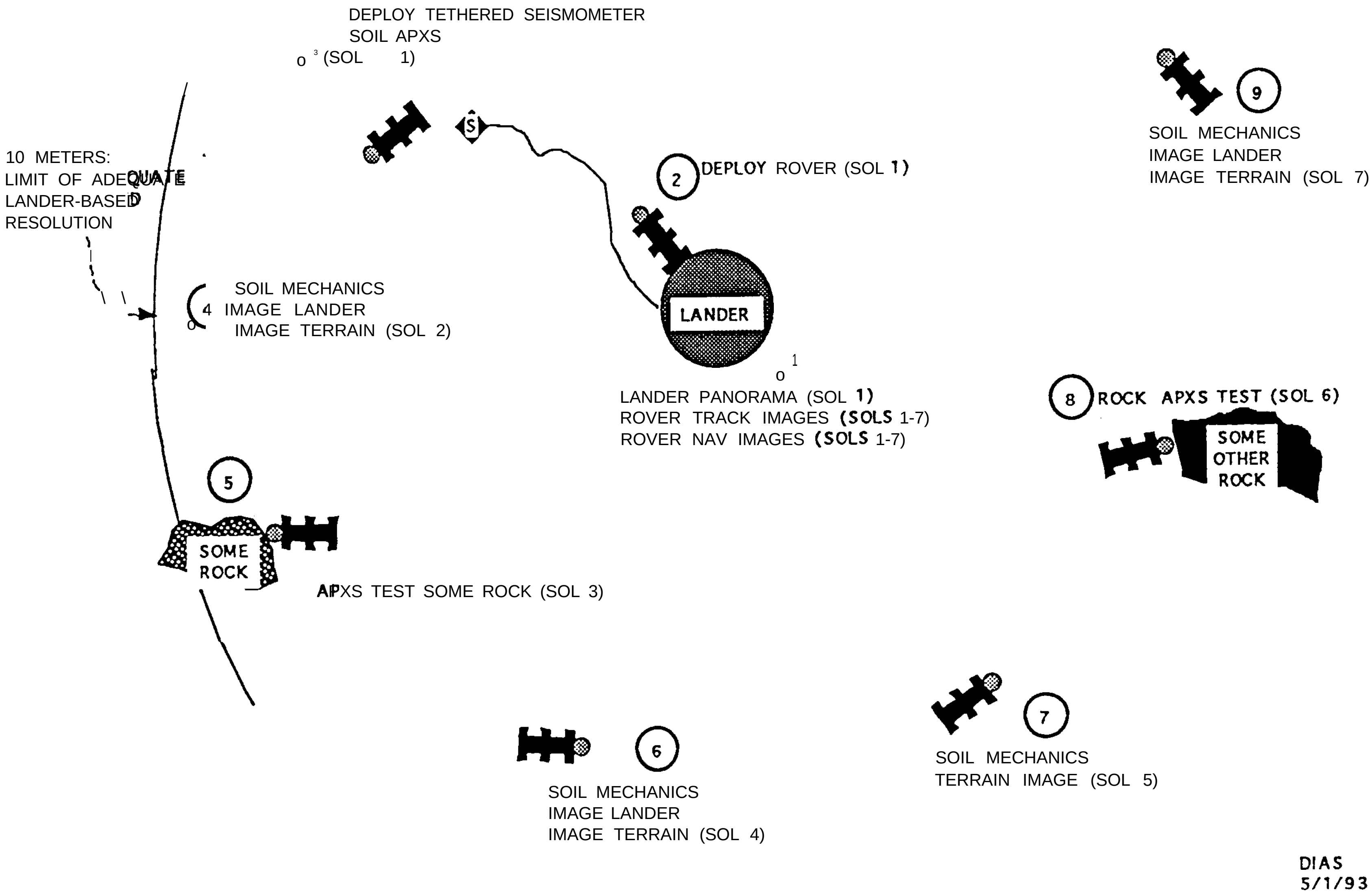


FIGURE ~~4.~~ 3 ROVER DESIGN PHILOSOPHY

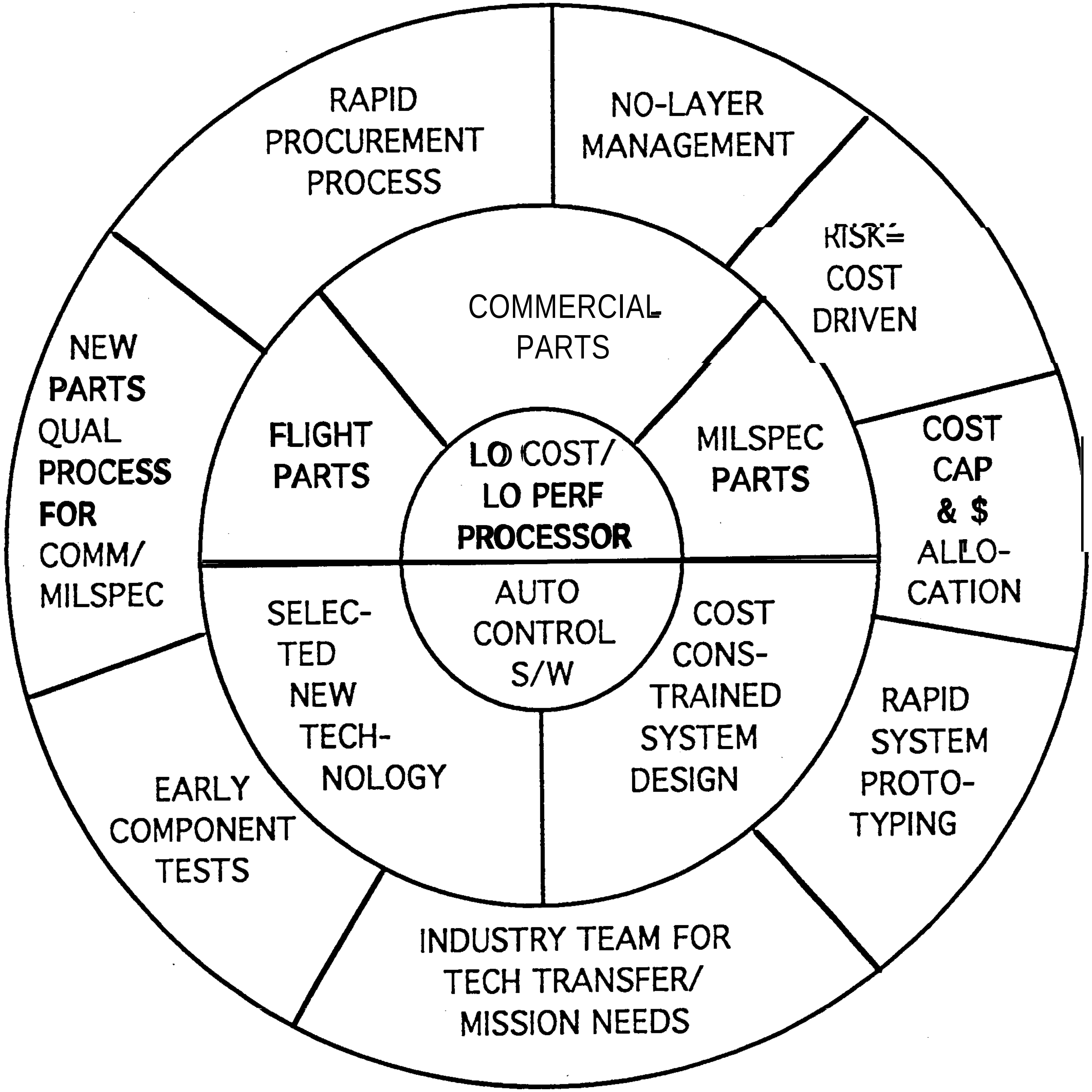


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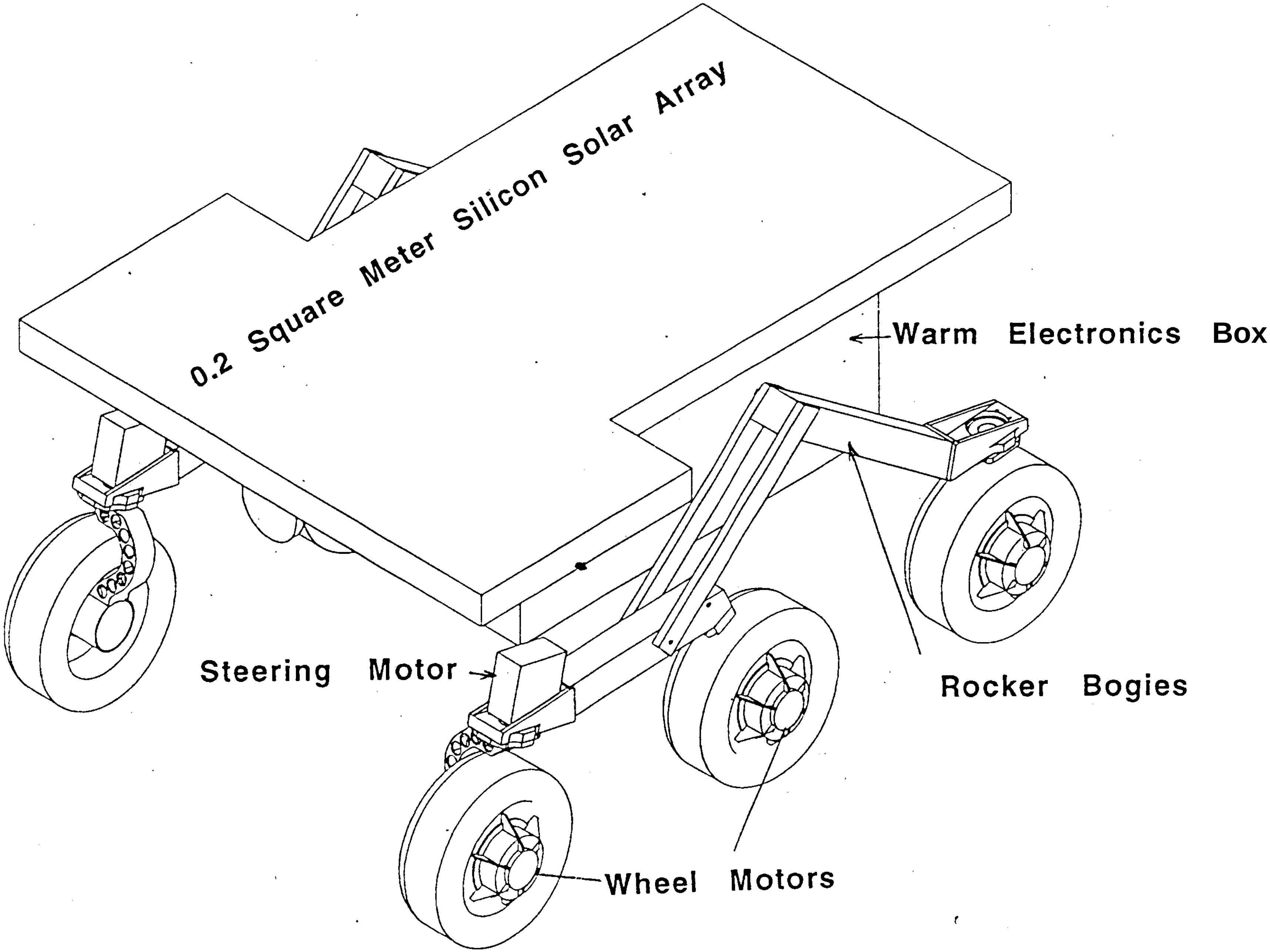
Figure ~~7.~~ Rover configuration



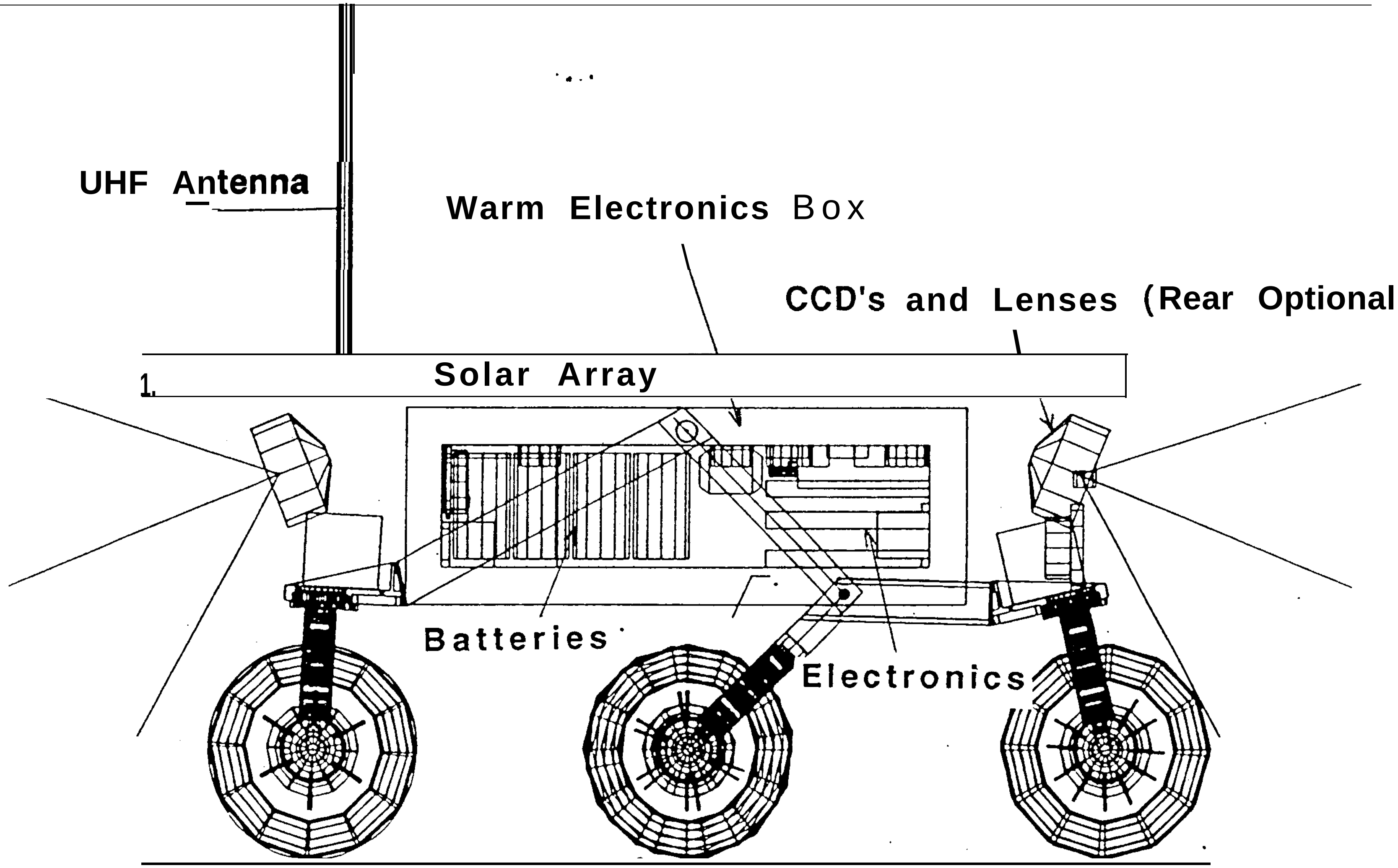



Figure ~~8~~. 5 Rover Configuration Side View

ATTACHMENT 3

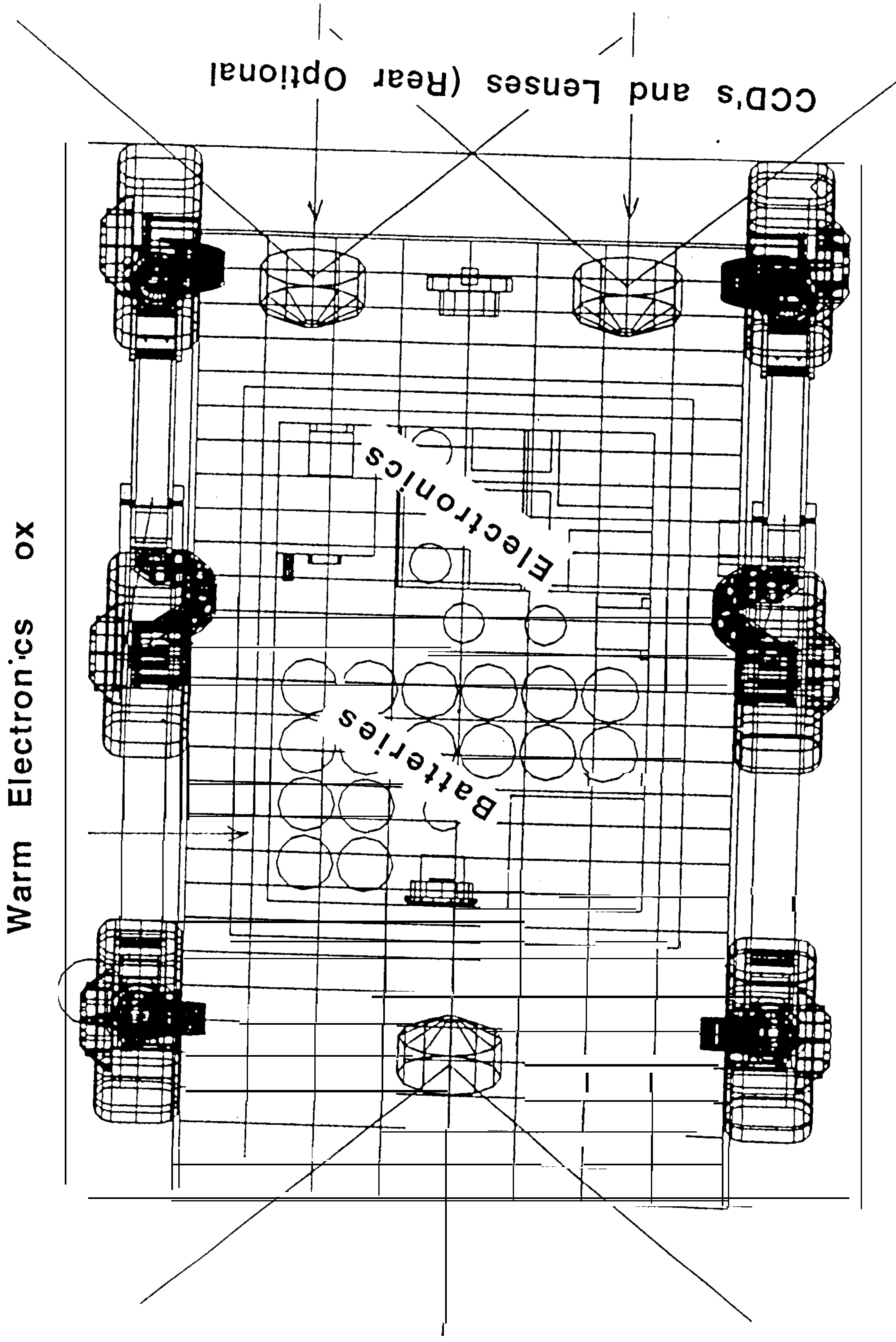



Figure 9. Rover Configuration Top View

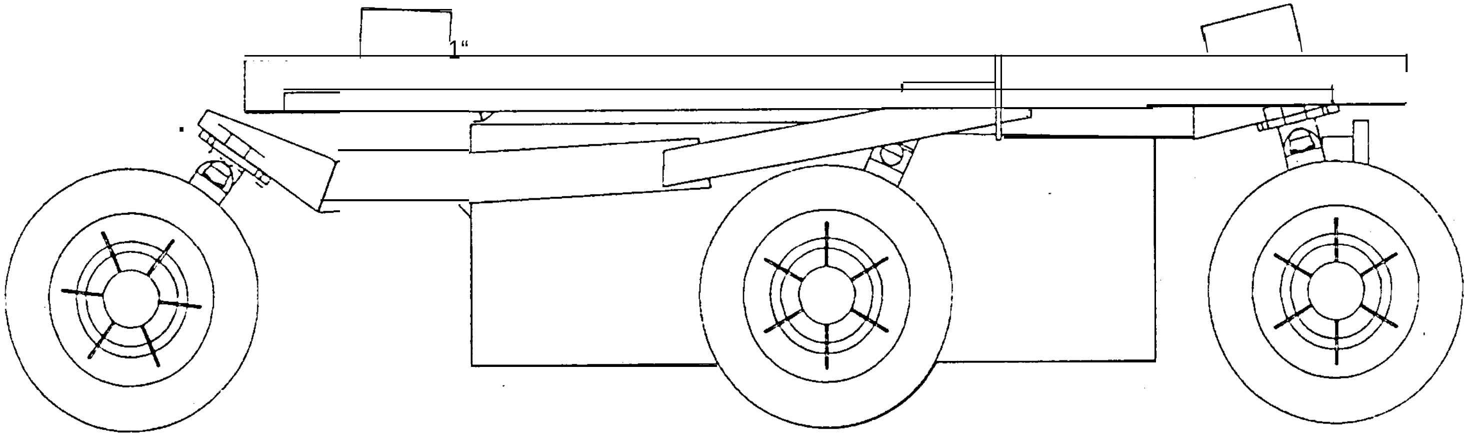


Figure ~~10~~. Stowed Configuration

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**Figure ~~11.~~ 8 Control Schematic**